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Safety in Earth Orbit Study

Contract Summary

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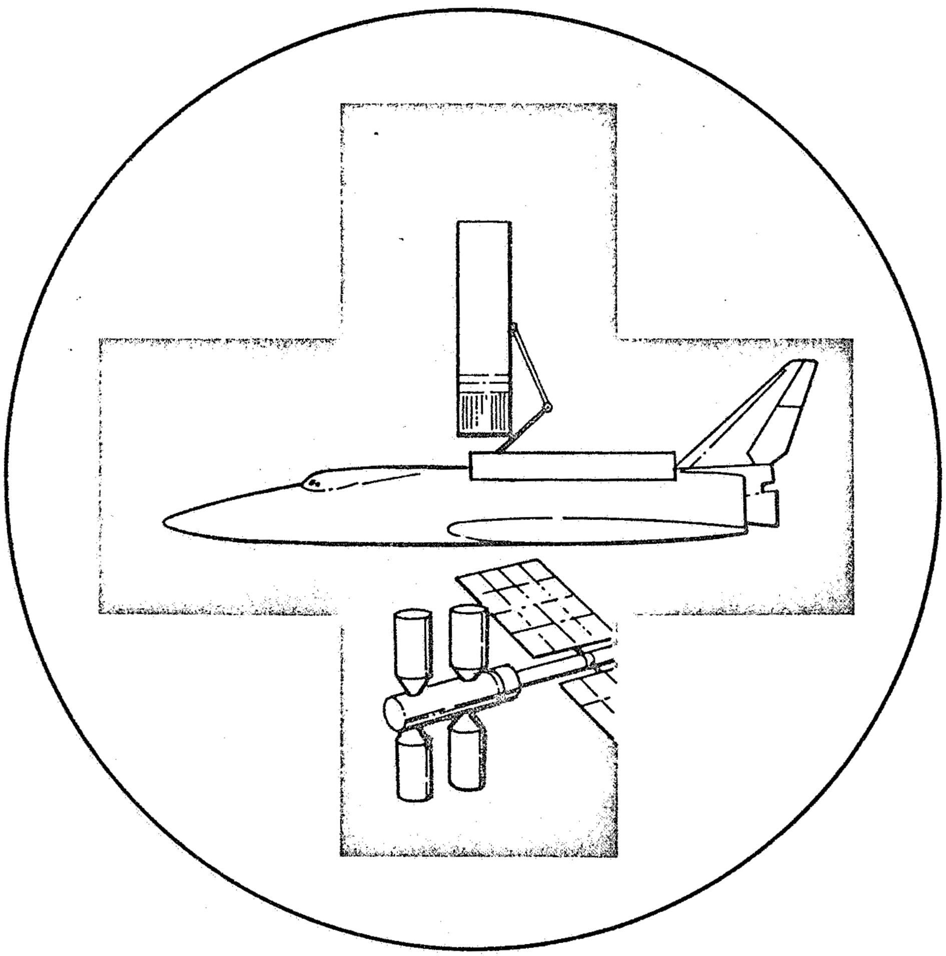

JULY 12, 1972

Space Division
North American Rockwell

12214 Lakewood Boulevard Downey, California 90241

MSC-04478
SD 72-SA-0095

FINAL REPORT

Contract Summary

Safety in Earth Orbit Study

JULY 12, 1972

Contract NAS9-12004

Approved by

G. S. Canetti
Study Manager

Space Division
North American Rockwell

FOREWORD

Final documentation of the Safety in Earth Orbit Study is submitted by the Space Division of North American Rockwell Corporation to the National Aeronautics and Space Administration, Manned Spacecraft Center, Houston, Texas, in compliance with DRL Line Items 3 and 4 of NASA-MSC Contract NAS9-12004.

The study was performed for the NASA Manned Spacecraft Center by the Space Applications Program organization at the Space Division of North American Rockwell. Mr. P. E. Westerfield of the Safety Office was the NASA technical manager.

Documentation of the study results is as shown in the following table.

DRL Line Item	Title	NR-SD Report No.
4	Contract Summary	SD 72-SA-0095
3	Final Report	
	Volume I - Technical Summary	SD 72-SA-0094-1
	Volume II - Analysis of: Hazardous Payloads, Docking, On-Board Survivability	SD 72-SA-0094-2
	Volume III - Analysis of: Tumbling Spacecraft, Escape and Rescue	SD 72-SA-0094-3
	Volume IV - Space Shuttle Orbiter Safety Requirements and Guidelines On-Orbit Phase	SD 72-SA-0094-4
	Volume V - Space Shuttle Payloads Safety Requirements and Guidelines On-Orbit Phase	SD 72-SA-0094-5

ACKNOWLEDGEMENTS

The guidance of Mr. P. E. Westerfield, the NASA technical manager, is gratefully acknowledged. His efforts were directed constantly at helping the study team to improve the quality of the study.

The comments, always constructive, of Mr. H. Schaefer, NASA Headquarters, and of Mrs. R. N. Weltmann, Lewis Research Center, also significantly improved the quality and readability of the study outputs.

Personnel at North American Rockwell who participated in the study are:

All tasks	- R. E. Altenbach
Hazardous Payloads	- L. K. Relyea
Docking	- G. O. Mount, Jr
On-board Survivability	- B. L. Felmet and J. W. Patrick
Tumbling Spacecraft	- A. Cormack III, A. N. Moore and B. U. Mahr
Escape and Rescue	- C. C. Harshbarger and B. U. Mahr

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1.0 INTRODUCTION

Most of the manned spaceflight programs planned by NASA for the late 1970's and 1980's are concentrated on earth orbital operations. These will use the shuttle and a variety of manned and unmanned payloads delivered to orbit by the shuttle.

This 12- month study examined five specific safety issues associated with these operations. The study logic used is shown in Figure 1. The five issues were studied as five separate tasks in the order shown. Hazards analyses were used on the first three tasks only.

This Contract Summary Report presents the significant results for each of the five safety issues in Section 2.0. Supporting research and technology requirements are summarized in Section 3.0, and suggestions for further effort to be undertaken by NASA are given in Section 4.0.

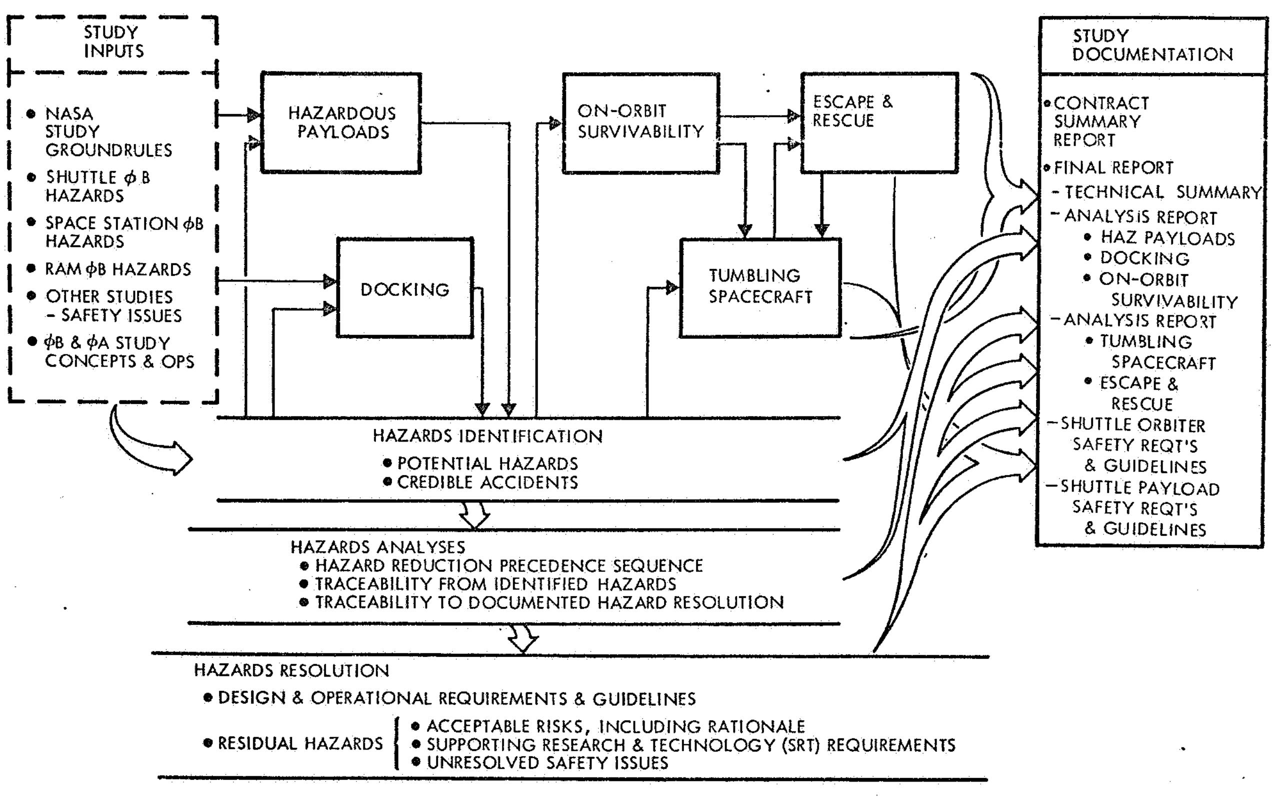


Figure 1. Study Logic

1.1 SCOPE

The study scope covered the vehicles shown in Figure 2.

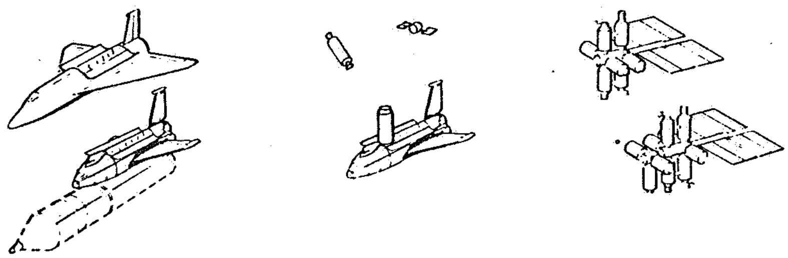


Figure 2. Vehicles Considered in Study

Initial tasks were based on the integral tank shuttle orbiter, but emphasis was later switched to the drop tank orbiter as this concept developed. The assumptions made were broad enough that no results were invalidated by this change.

Shuttle payloads considered included manned and unmanned sortie payloads (i.e., attached to the orbiter), satellites delivered to earth orbit, and potential upper stage vehicles, such as the Tug, Agena, Centaur, etc., used to deliver unmanned payloads to orbits beyond the orbiter's capabilities.

The space stations considered were modular stations delivered to earth orbit and assembled by the orbiter. Initial 6-man versions and growth versions with up to 12 men, as defined in recent Phase B studies, were studied.

Within the scope of the vehicles described, the study is bounded by the following ground rules:

- The main concern is personnel safety. A lesser emphasis was placed on avoiding damage to or loss of the vehicles.
- The analysis was confined to the manned on-orbit phase of missions.
- The study results cover only the five specific concerns of the study. They must not be assumed to cover all safety aspects of the relevant vehicles.

1.2 STUDY OBJECTIVES

The study was concerned with five specific issues. These issues and their objectives are:

1. Hazardous payloads. The objective was to identify hazards associated with certain orbiter payloads and to determine safety requirements and guidelines.

2. Docking. The objective was to compare a number of different approaches for docking an orbiter to a space station, and to recommend the methods preferred from a safety point of view.

3. On-board survivability. The objective was to determine the configurational and other requirements for the orbiter, sortie module, and space station to allow personnel to survive on-board emergencies.

4. Tumbling spacecraft. The purpose was to determine practical means for arresting the motion of out-of-control tumbling spacecraft by external means, or to allow on-board personnel to escape from a spacecraft if tumbling cannot be arrested.

5. Escape and rescue. The objective was to determine the applicability of previous or new concepts for escape, rescue, and bail-out type survivability to the orbiter, sortie modules, and space station.

1.3 RELATIONSHIP TO OTHER STUDIES

The Safety in Earth Orbit study was performed in the context of a wide range of related studies. This relationship is shown in Figure 3.

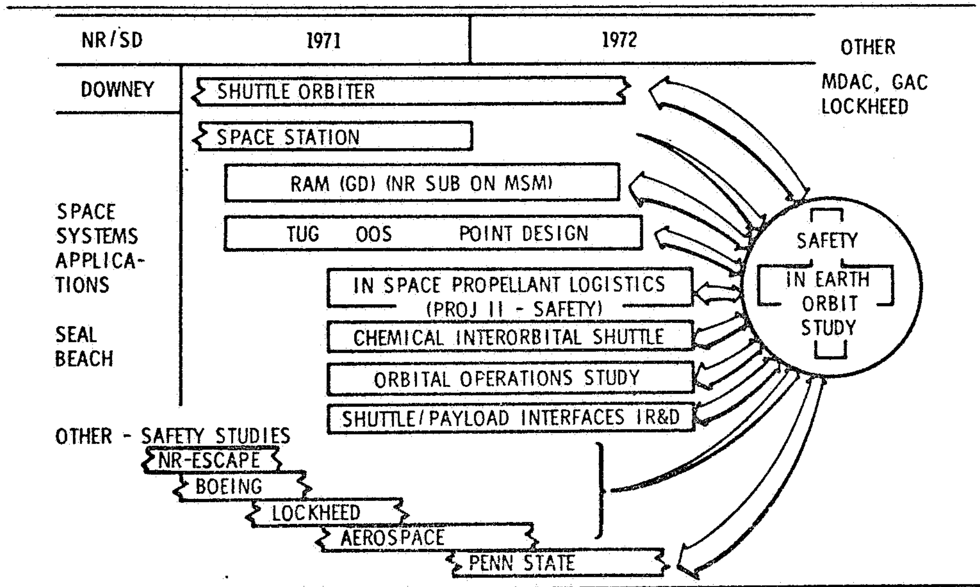


Figure 3. Relationship to Other Studies

The most important of these studies are the Phase B studies on the space station, shuttle, and RAM (Research and Application Modules). Phase A studies on the tug, orbit-to-orbit shuttle (OOS), and the chemical interorbital shuttle, and systems studies on the Orbital Operations and the In-Space Propellant Logistics Study (ISPLS) provided additional information on relevant hardware elements and also on operational modes.

A good interchange of information was possible with all the concurrent studies for which NR was a prime contractor (subcontractor on the RAM). The interchange of information and ideas generally flowed in both directions. This interchange was particularly fruitful with the Orbital Operations study and the safety portion (Project II) of the ISPLS study.

Additional safety background was obtained from earlier safety studies by Boeing (on the space station), Lockheed (on the shuttle), and from ongoing studies by the Aerospace Corporation (on the shuttle and on escape and rescue). A particularly useful cooperative effort was also established with Pennsylvania State University on the dynamics of tumbling spacecraft.

2.0 SIGNIFICANT RESULTS

The five issues of the study were analyzed as five separate but related tasks during the study. The scope of each of these five tasks and the more significant results and conclusions are presented for each task in Sections 2.1 to 2.5.

Since the scope and the objective of each task was substantially different, a variety of approaches and outputs was involved. These are summarized in Table 1.

Table 1. Approaches and Outputs for Each Task

Task	Approach	Main Outputs
Hazardous payloads	• Hazards identification • Hazards analyses	• Safety requirements and guidelines
Docking	• Hazards identification • Hazards analyses • Systems tradeoffs	• Safety requirements and guidelines • Docking system recommendations
On-board survivability	• Systems analyses • Hazards analyses	• Configurational and other requirements • Safety requirements and guidelines
Tumbling spacecraft	• Dynamics analysis • Systems analyses	• Safety device conceptual designs
Escape and rescue	• Systems analyses	• Escape and rescue system recommendations

Fifty-nine hazards analyses were performed in the first three tasks, and approximately 450 safety requirements and guidelines were developed. (Requirements are mandatory; guidelines are discretionary.) These have been documented in specification format in two requirements and guidelines documents, one for the shuttle orbiter and one for the shuttle payloads.

2.1 HAZARDOUS PAYLOADS

Many different kinds of cargo will be carried into orbit in the cargo bay of the shuttle orbiter. In this task, three areas of safety concern were analyzed. These are:

- Delivery, deployment, and retrieval of upper stage vehicles such as the Agena, Centaur, Transtage, Burner II, Apollo service module, and Tug
- Transport of hazardous fluid vessels
- Cargo handling and transfer

The task consisted of identifying potential hazards and performing hazards analyses. The principal conclusions and recommendations reached are:

- The orbiter design is extremely sensitive to even small explosions in the cargo bay. Uncontained explosions equivalent to as little as 5 g (0.01 lb) of TNT may result in exceeding the structural design limit of the cargo bay structure (14 kN/m^2, 2 psi) from blast overpressure. By comparison, a hand grenade is equivalent to 10 g (0.025 lb) of TNT, and a fully loaded Centaur to approximately 2700 kg (6000 lb) of TNT.
- Any structural failure of a loaded upper stage vehicle while in the orbiter cargo bay which results in large leaks of both fuel and oxidizer will almost certainly be catastrophic to the orbiter. The energy content of even the smallest liquid propellant upper stage vehicle, if released suddenly, is far more than can be tolerated by the orbiter. Every effort must therefore be made to prevent structural failure of upper stage vehicles while in or near the orbiter. Remedial measures are not considered practical, and have not been recommended.
- The liquid contents of upper stage vehicles being returned to earth should be dumped to space before deorbiting the orbiter. The acceptable level of residual liquids and gas before returning to earth should be such that an insulation failure, leakage, or a crash landing will not result in overpressurization, fire, or a similar accident.
- If the leakage of large quantities of payload fluids into the orbiter cargo bay is considered credible, then additional venting of the cargo bay beyond that provided by the orbiter for normal venting may be required to avoid potential overpressurization of the cargo bay. This may need to be considered and provided for individually for each payload which contains large quantities of fluids.

- Capability should be provided for the orbiter to deorbit, reenter, and land with a fully loaded upper stage vehicle. It is not recommended that reduced factors of safety be considered for this situation, but the reentry and landing load criteria should be less severe than the normal design cases (e.g., 2 σ conditions instead of 3 σ) for this maximum weight condition.

- Upper stage vehicles must be man-compatible; i.e., man rating safety criteria must be applied to systems and functions of the upper stage vehicle which could create a hazard to the orbiter while the upper stage vehicle is in or near the orbiter. These criteria, while not currently defined, must be defined consistently for the shuttle and for upper stage vehicles. One possibility is that a flight test of the upper stage vehicle be performed in the shuttle using fluids which are physically similar to the propellants but which do not react chemically. Such a flight test may be cost-effective because it can replace much of the ground qualification testing.

- Launching space station or sortie modules pressurized at 1 atmosphere can present the orbiter with a considerable hazard. A typical module has an explosive potential of 10 kg (22 lb) TNT equivalent in the vacuum environment of space. If this energy is rapidly released, e.g., by structural failure of the module, the resulting blast and shrapnel would cause catastrophic damage to the orbiter.

- Many different fluids, of varying degrees of hazards and in varying quantitieis, are currently planned for transportation to and from space by the orbiter. An adequate level of safety appears possible to both the personnel involved and the spacecraft. More specific safety features than defined in the study must await a more detailed definition of the spacecraft, payloads, and their planned operations than is currently available.

- Cargo handling in space presents some specific hazards associated with the zero-g environment and with the limited remedial and escape provisions available. In addition to normal safety features required on the ground, specific requirements and guidelines, such as tethering of heavy cargo at all times, double-containing hazardous cargo, and providing mechanical assist where propulsive forces are possible, have been identified.

2.2 DOCKING

The Space Station Program Phase B studies identified a concern as to the best way to effect docking between the shuttle orbiter and large vehicles such as the space station. In this task the safety aspects of various docking modes and systems were compared to determine the preferred approaches from a safety point of view.

The docking modes considered are illustrated in Figure 4. These are the orbiter-to-station mode, in which the two large vehicles dock to each other, and the free-flying mode, in which the module being transferred free-flies between the orbiter and space station and is the only vehicle that docks to the orbiter or station.

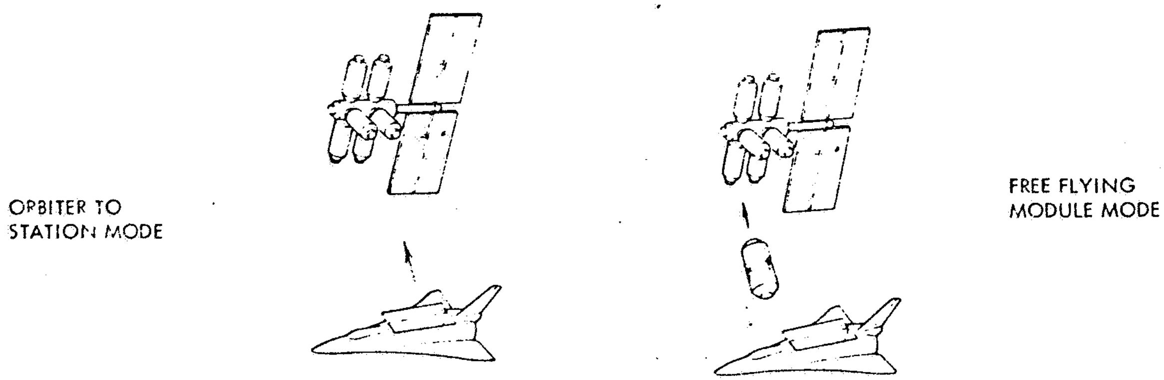


Figure 4. Docking Modes Considered

The docking systems considered are illustrated in Figure 5. These are the direct docking system, as used on the Apollo; manipulator docking, as planned on the orbiter and station; and an extendable tunnel docking system, as considered on the Apollo at one time, which provides a separation of perhaps 3 m (10 ft) at initial contact.

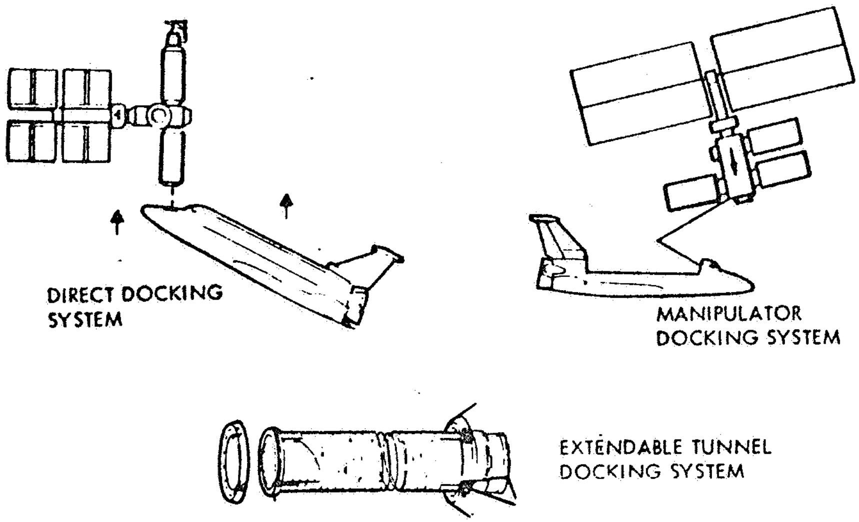


Figure 5. Docking Systems Considered

The docking modes and systems were analyzed and evaluated using the following criteria:

- Potential for personnel loss
- Risk (probability and criticality) of remaining hazards
- Design impact for safety requirements
- Capability to deal with emergency docking

Conclusions and recommendations on docking modes are:

- The orbiter-to-station docking mode has more potential of causing major damage to the orbiter and/or station than the free-flying docking mode, but does not directly lead to personnel loss. The free-flying docking mode has a potential for personnel loss when used to transfer personnel between orbiter and station, but precludes the possibility of a single accident resulting in loss of both the orbiter and station.

- The orbiter-to-station docking mode should be considered acceptable from the safety point of view with any of the acceptable docking systems.

- The use of the free-flying docking mode for the transfer of manned modules should be rejected for normal operations because of the potential for personnel loss. This mode may be used in emergencies.

- If mini-tugs (such as remote maneuvering units) or modules with self-contained propulsion, control, and docking capabilities (such as the space tug) are developed for other purposes and are available, their use in transferring modules or payloads between orbiter and station should be considered as an acceptable mode. Use of this free-flying mode for unmanned payloads, in conjunction with the use of the orbiter-to-station mode for all manned modules, has significant safety advantages.

Conclusions and recommendations on docking systems are:

- The direct docking, extendable tunnel, and manipulator docking systems can be made adequately safe, and should all be considered as acceptable docking systems from the safety point of view.

- The direct docking system has the greatest potential for inadvertent collision because of the close proximity of the docking vehicles. The manipulator docking system has the minimum potential for inadvertent collision between vehicles because of the relatively large separation distance at initial capture, but has more failure modes which can result in inadvertent contact and damage.

- The direct docking can perform a time-critical emergency docking quicker than the other systems. The manipulator docking system has more potential for docking with an out-of-control tumbling or spinning spacecraft.

- Use of the manipulator for transferring modules with men in them should be rejected as a practical option for personnel transfer in normal operations because of the high potential for personnel loss. The method is acceptable for transfer of unmanned modules or for emergencies.

2.3 ON-BOARD SURVIVABILITY

Many emergencies are possible in manned spacecraft for which the survival of the personnel must be ensured on-board the spacecraft until a normal situation can be restored or the personnel can be rescued. The purpose of this task was to analyze the personnel traffic patterns, escape routes, and compartment isolation from a safety standpoint for the orbiter, sortie modules, and the modular space station, and to determine the configurational and other requirements to ensure on-board survivability.

Seven candidate configurations of the orbiter were considered, consisting of various combinations of crew compartment, passenger compartment, and airlock. These are shown schematically in Figure 6. The configuration resulting from the Phase B studies, consisting of a single combined crew/passenger compartment and an airlock, is represented by Configuration 2. If the airlock is made large enough to accommodate all on-board personnel, however, it may be considered to be like Configuration 3.

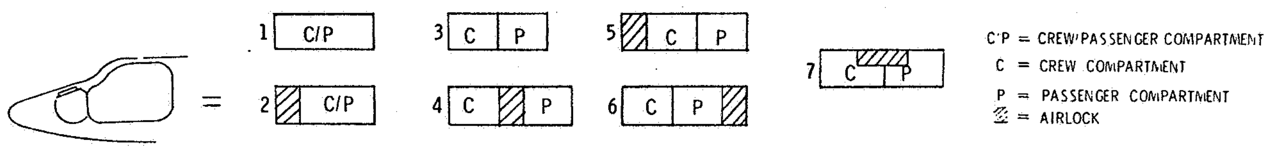
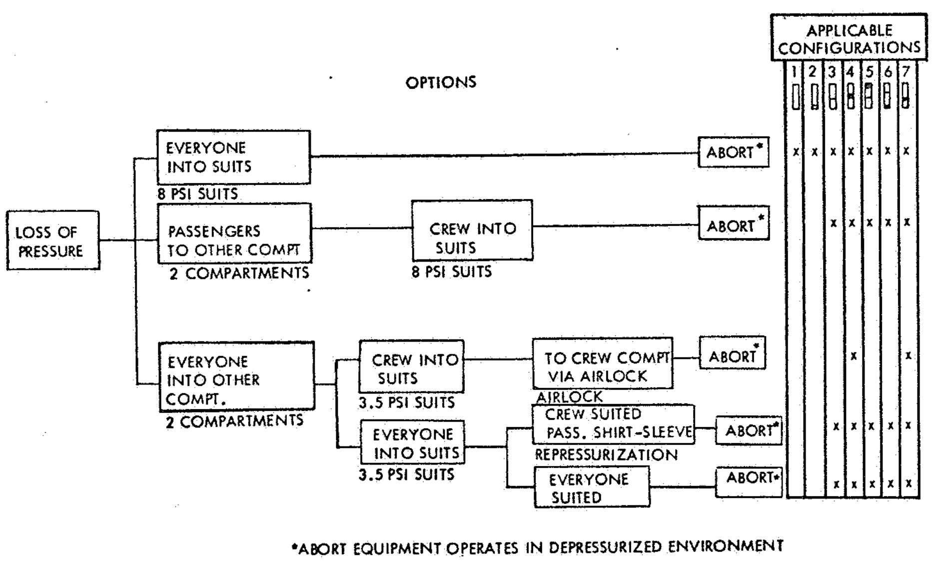


Figure 6. Candidate Orbiter Configurations

Many operational options are available for coping with emergencies such as fire, toxicity, explosions, and depressurization. The various options require different combinations of compartmentation, airlock capability, and pressure suits. The options available in case of loss of pressure on-board the orbiter with an unmanned payload are shown in Figure 7. This figure



*ABORT EQUIPMENT OPERATES IN DEPRESSURIZED ENVIRONMENT

Figure 7. Options for On-Board Survivial following Depressurization On Orbiter with Unmanned Payload

also shows some of the requirements associated with each option, and the suitability of each option to the seven candidate orbiter configurations. The term "8 psi suits" refers to pressure suits which can be donned by personnel acclimated to a one atmosphere environment and be exposed to low pressure within a few minutes (approximately 5 min.) of the occurrence of an emergency. Suits of 3.5 psi require a few hours prebreathing of pure oxygen, at one atmosphere pressure, to avoid decompression sickness (the bends). All options require the equipment required for abort to operate and be operable in a depressurized environment.

When all the configurations are analyzed against all the identified emergencies, an integrated set of options can be developed. These options are shown in Figure 8 for the seven configurations. The five different options are identified by the letters A to E, and differ basically in the quantity and type of pressure suits required, and whether or not a separate refuge compartment is available.

Also shown in this figure are the safety evaluations for the various options. All options shown can deal with the emergencies considered, but Configurations 1 and 2, which only have one compartment, do not provide a refuge compartment in case of an emergency which renders the compartment uninhabitable either shirtsleeve or suited. These two configurations are, therefore, rated acceptable, provided 8 psi suits are carried on-board for all personnel. The difference between the "good" and "best" options is that the latter allow for a 2-minute reaction time (i.e., assess situation and exit to another compartment) instead of a 7-minute reaction time (assess situation and don 8 psi suits).

CONFIGURATION	OPTION	PRESSURE SUITS QTY.	PRESSURE SUITS TYPE	SAFETY FACTORS REACTION TIME*	SAFETY FACTORS REFUGE COMPT.	SAFETY RATING
1. C/P	A	ALL	8 PSI	7 MINS	NO	ACCEPTABLE
2. C/P	A	ALL	8 PSI	7 MINS	NO	ACCEPTABLE
3. C P	B	2	8 PSI	7 MINS	YES	GOOD
	C	ALL	3.5 PSI	2 MINS	YES	BEST
4. C P	D	2	3.5 PSI	2 MINS	YES, IF ACCESSIBLE	POOR **
5. C P	B	2	8 PSI	7 MINS	YES	GOOD
	C	ALL	3.5 PSI	2 MINS	YES	BEST
	D	2	3.5 PSI	2 MINS	YES	BEST
6. C P	B	2	8 PSI	7 MINS	YES	GOOD
	C	ALL	3.5 PSI	2 MINS	YES	BEST
	E	2	3.5 PSI (EVA)	2 MINS	YES	BEST
7. C P	D	2	3.5 PSI	2 MINS	YES	BEST

* REACTION TIME TO ACHIEVE SAFETY: 7 MINS TO DON SUITS; 2 MINS TO EGRESS TO REFUGE COMPT
**AIRLOCK PROBLEM CAN PREVENT ACCESS TO CREW COMPARTMENT

Figure 8. Comparison and Evaluation of Options

Conclusions and recommendations reached on the final Phase B orbiter configuration (No. 2) are:

- Quick-donning pressure suits which do not require prebreathing (8 psi suits) should be provided for all on-board personnel.
- The crew/passenger compartment should be divided into two sections by a partition which can exclude smoke and fumes, and can provide protection against excessive heat from a fire. These sections can provide temporary refuge until corrective measures can be taken.

- All equipment required for return to earth should be capable of operating in a depressurized environment, and of being operated by the crew in pressure suits.

- Capability should be provided for returning from EVA directly into the crew/passenger compartment.

- Provided the above recommendations are implemented, the airlock is not required for safety purposes. It should be available, possibly as a payload item, on missions for which EVA is planned.

- If the airlock is capable of accommodating all passengers in emergency shirtsleeve conditions through deorbit and entry, then 8 psi suits are required only for the orbiter crew on those missions. The passengers have time to return to their seats for landing after reaching low altitudes.

Similar analyses carried out on manned sortie modules attached to the orbiter led to the following conclusions and recommendations:

- A sortie module consisting of two separate pressurized modules does not have any significant safety advantages compared to a single module version. In both cases, the orbiter is available as a separate refuge compartment.

- No safety requirement exists for an airlock between the sortie module and the orbiter.

- A means of emergency exit (dual egress capability) should be provided in sortie modules; for example, by a longitudinal floor providing independent personnel routes above and below the floor.

- Emergency accommodations should be provided in the orbiter for all passengers during an abort.

Analysis of the space station during assembly, normal operations, and resupply by an orbiter showed that the following criteria should be applied:

- Access to two or more shirtsleeve entrances into normally habitable compartments of more than 25 m^3 (880 ft^3) in volume should be immediately available from each of the other normally inhabited compartments.

- Capability should be provided for the emergency shirtsleeve survival of all on-board personnel until the next resupply or emergency shuttle flight following the loss of access to any one module/compartment and the loss of equipment and supplies in that module/compartment. If the loss of the module/compartment divides the station into two or more isolated habitable sections, then each section should provide the survival capability for all on-board personnel, including an available docking port.

2.4 TUMBLING SPACECRAFT

Uncontrolled tumbling of a spacecraft following loss of its capability to control attitude is one of the most critical emergency situations that could arise in space. Deorbit, reentry, or docking would not be possible under these conditions. Such a situation could be catastrophic, and result in loss of both the vehicle and its occupants.

The purpose of this task was to examine possible methods for arresting the motion of an out-of-control tumbling spacecraft by means external to the vehicle in order to save the on-board personnel and, if possible, the spacecraft; and to determine the feasibility and establish requirements for personnel escape in the event the tumbling cannot be arrested. Four types of spacecraft were considered: the integral tank shuttle orbiter, the drop tank shuttle orbiter, the space station, and small space vehicles such as individual sortie modules or space station modules. The rescuing vehicle was assumed to be a shuttle orbiter with an appropriate emergency payload. All the concepts considered for arresting the tumbling could, however, be used equally well in a remotely controlled mode from an unmanned tug brought up in a shuttle orbiter.

Worst case tumbling conditions were estimated by Pennsylvania State University under a NASA contract, based on a variety of postulated torque-producing situations. The maximum angular tumbling rates established are summarized in Table 2. Hardover gimbaled engines and inadvertent RCS firing were limited to times of 15 seconds and 60 seconds, respectively, as being maximum likely crew reaction times. The escaping atmosphere and escaping gases or fluids cases are based on worst case conditions of leakage with the maximum possible moment arm. Collision velocities of up to 1.5 m/sec (5 fps) were assumed.

Table 2. Summary of Maximum Tumbling Rates in RPM

Source	Modular Space Station	Small Space Vehicle	Integral Tank Orbiter	Drop Tank Orbiter
Collisions	0.6 to 2.1	4.7 to 14.7	0.3 to 1.1	0.5 to 1.4
Escaping atmosphere	8.9	52	Not critical	Not critical
Escaping gas or fluids	0.4 to 4.0	Not critical	Not critical	Not critical
Hardover gimbal	Does not apply	Does not apply	1 to 2	1 to 2
Malfunctioning thruster	0.03	0.5 to 4.0	0.5 to 4.0	Not critical

Twenty-three different concepts for arresting the tumbling were considered. The most practical of these were the water jet concept and the stick-on rocket concept.

The water jet concept, illustrated in Figure 9-A, consists of a water tank of about 3 m (10 ft) diameter carried on board the rescue orbiter as a rescue kit. A variable pressure pump, electrically driven, produces a finely atomized jet of water through one of three different size nozzles. The orbiter is pointed so that the water impinges on the tumbling spacecraft to cancel out its angular momentum. The water jet is driven at 30 to 120 m/sec (100 to 400 fps), and is spread out sufficiently at impact to produce very low pressures on the order of 500 N/m^2 (10 psf) on the tumbling vehicle. The water impinges as ice particles which are finely divided and, therefore, do not damage the surfaces. No debris is left in orbit. The tumbling motion can be arrested for the worst case considered with 4 hours of jet impingement.

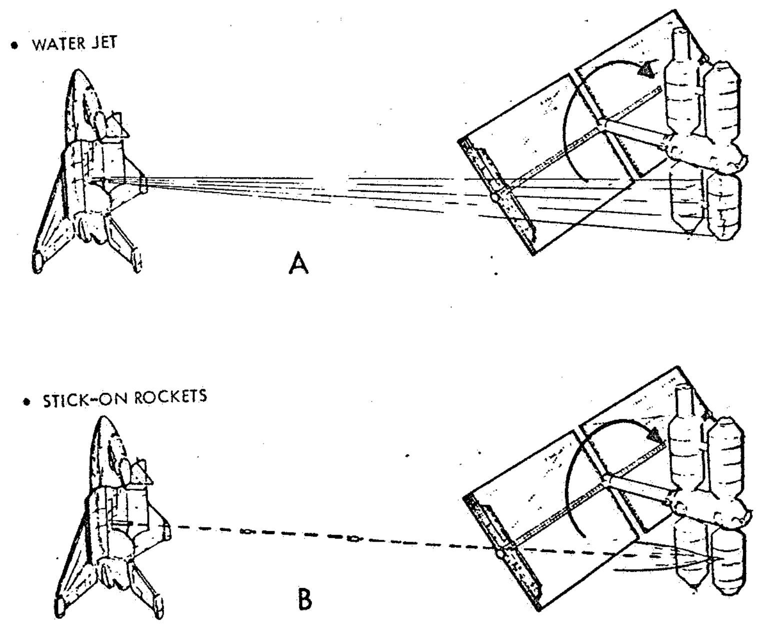


Figure 9. Water Jet and Stick-On Rocket Concepts

The stick-on rocket concept, illustrated in Figure 9-B, consists of a large number of small solid rocket motors of about 10 kg (22 lb) each. These are directed at low speed toward the tumbling spacecraft by a "gun" on the rescuing orbiter. Simple computer functions are required to determine the correct timing for firing the rockets so as to hit the desired portion of the tumbling vehicle. The spin-stabilized rockets attach themselves to the tumbling vehicle by serrated friction pads, or by special penetration devices. A trigger ignites the rockets upon contact. As many as thirty rockets may be required to arrest the worst case motion of the largest vehicles. If a few rockets are incorrectly aimed, the motion of the vehicle will be adversely affected by a small amount. Any rockets that do not become attached to the tumbling vehicle are fired by a timer to prevent them from becoming a hazard to other spacecraft.

For both these concepts a single rescue orbiter is required to arrest the worst tumbling cases identified in Table 2.

If it is not possible to arrest the tumbling motion, the on-board personnel must don suits, escape from the tumbling vehicle by EVA, and be rescued by the rescue orbiter. Two problems were investigated. These were: (1) whether personnel can exit from the tumbling vehicles without recontact with the structure, and (2) how the personnel can arrest their own tumbling motion after exiting so that they can safely be picked up by the rescuing orbiter.

Analysis shows that, for rotation of the vehicles about their geometric axes, suitable exits and procedures exist for men to exit from the spacecraft without recontact. For some cases a small pushoff, well within man's physiological capabilities, may be required. For general tumbling about all three geometric axes simultaneously, the analysis becomes prohibitively complex, but extrapolation from the single axis analysis indicates that simple procedures should be practical.

Two simple schemes for slowing down the men's tumbling motion to small enough values for rescue (about 3 rpm) are shown in Figure 10. In the first one the men jump out in pairs, holding a light cable between them. When free of the spacecraft they let the cable out. When the cable is extended to about 3 m (10 ft), their angular rates are reduced to less than 1 rpm. In the second scheme the men leave singly and let out a cable with an appropriate mass tied to its far end. When the angular rate is sufficiently small they can release the cable.

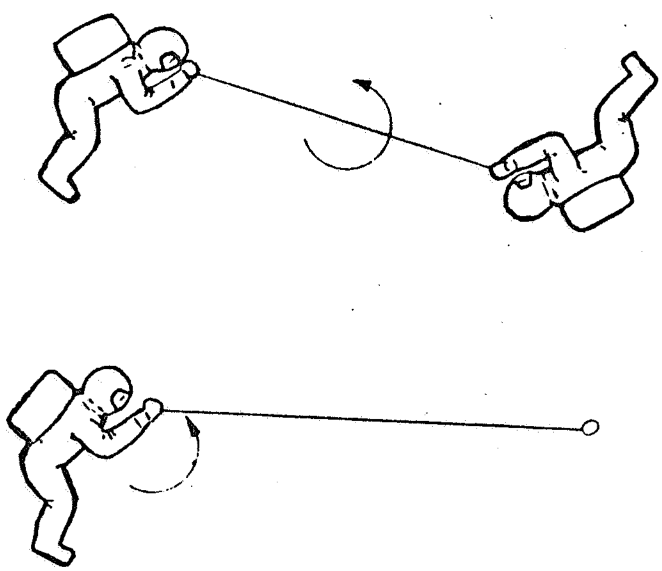


Figure 10. Concepts for Reducing Personnel Tumbling Rates

2.5 ESCAPE AND RESCUE

Crew safety is of prime importance in the design of any manned system, and many provisions are incorporated to prevent accidents and to deal with emergencies. The ultimate safeguard, however, consists of provisions for escape or rescue from a spacecraft which can no longer safely sustain the on-board personnel.

The purpose of this task was to examine the applicability of various existing escape and rescue concepts to shuttle and space station operations, and to recommend adaptations of these, or completely new concepts as necessary.

Eleven existing escape concepts (on-board life-boat vehicles with atmospheric reentry and landing capability), two rescue concepts (requiring launch of a rescue vehicle from the ground and its return to earth), and five survivability concepts (life-boat vehicles requiring rescue in orbit) were identified. The evaluation of these concepts is shown in Table 3. Costs and weights refer to a capability for six or more men. Multiple vehicles are assumed where their crew size is less than six men.

Table 3. Evaluation of Escape, Rescue, and Survivability Concepts For Six Men

Concept	Crew Size	Shirt-Sleeve	Cost ($M)	Technology	Development Risk	Launch Vehicles	Recovery	Payload** Impact
Escape								
Airmat	2	No	93	New	High	No	Water	Low
Rib stiffened	3	Yes	103	New	High	No	Water	Low
Paracone	1	No	84	New	High	No	Water	Low
Moose	1	No	100	New	High	No	Water	Low
Encap	1	No	100	New	High	No	Water	Low
Egress	1	Yes	79	New	Medium	No	Water	Medium
Life raft	3	No	86	New	High	No	Water	Low
Lifting body	3	Yes	196	New	Medium	No	Water	Medium
EEOD	3	Yes	108	New	Medium	No	Water	Medium
Spherical heat shield	2	Yes	87	New	Medium	No	Water	Low
Apollo Escape CM	2-6	Yes	35	Current	Very low	No	Water	High
Rescue								
Shuttle	12	Yes	0-1 launch	None extra	Low	***only if needed	Shuttle	None
Apollo Rescue CSM	2-4	Yes	Very high	Current	Low(S-IB) Med(Titan)	Yes	Water	None
Survivability*								
Cocoon	1	No	Med-High	New	High	***Only if needed	Shuttle	Low
Sortie module	12	Yes	Med-High	Current	Medium		Shuttle	Low
Space Station Module	12	Yes	Med-High	Current	Medium		Shuttle	N/A
Apollo Survivability CM	8	Yes	Med-High	Current	Medium		Shuttle	High
Modular Survivability Vehicle (MSV)	12	Yes	Med-High	Current	Medium		Shuttle	Low

*Assumes shuttle used for rescue
**Low = 2000 kg (4500 lb), high = 4000 kg (9000 lb)
***Launch vehicles are used only if a rescue or survivability situation arises. Dedicated launch vehicles not required.

Shirtsleeve use and a two or more man (buddy) capability are considered prime safety requirements. Cost, technology, and program risk factors reduced the preferred choice to the following:

Escape:	2- to 6-man refurbished Apollo command module with deorbit retrorocket package
Rescue:	Shuttle booster and orbiter
Survivability:	Sortie module, space station module, modified Apollo command module, or new module, as found most cost-effective

The practical choices between these depend on whether shuttle rescue will be available, and if so, whether it will be quick enough to respond to credible emergencies. The choices and the recommendations are shown in Figure 11. These are summarized as follows:

- The shuttle orbiter should be the primary vehicle for dealing with emergencies of manned vehicles in earth orbit. A shuttle orbiter should be available for rapid emergency rescue whenever manned earth orbital flight is in progress. This need not be a dedicated rescue shuttle or orbiter, but a normal operational vehicle on which any of a variety of rescue kits could replace the planned payload in an emergency.

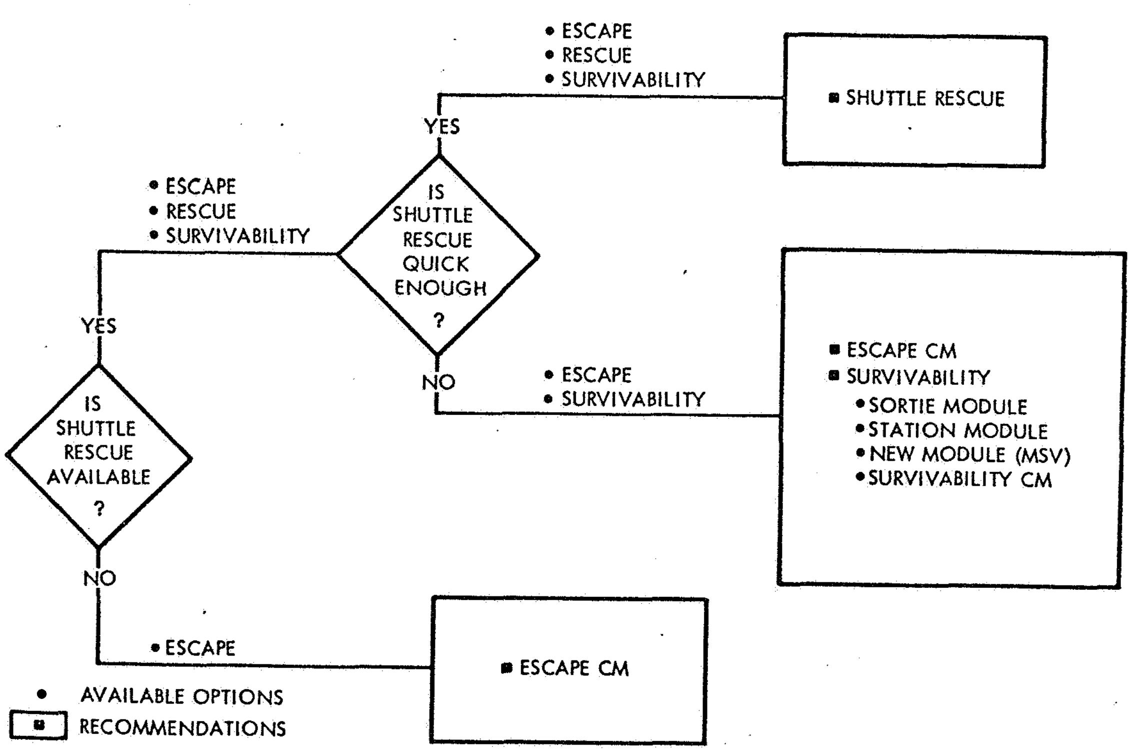


Figure 11. Escape, Rescue, and Survivability Options

- If there is a time period at the beginning of the shuttle program (or during the mature shuttle operational period) when shuttle rescue is not possible because of the nonavailability of a rescue shuttle, launch pad, or other reason, an Apollo command module (CM) should be carried in the orbiter cargo bay as an escape vehicle. This can be a refurbished command module with up to six seats (as required), and with capability for reentry from earth orbit and water landing. The CM should be pressurized at 8 psi to allow rapid shirtsleeve entry of the personnel without the danger of getting "bends." This escape CM is the most cost-effective of the escape and rescue vehicles considered.

- If a quicker escape or rescue capability is required than can be provided for by the emergency shuttle rescue, escape or survivability modules should be carried on-board each flight. These may be refurbished Apollo CM's, without reentry and landing capability, sortie or space station modules, or new survivability modules.

Figure 12 shows how an escape Apollo CM survivability module may be carried in an orbiter with a pallet sortie payload.

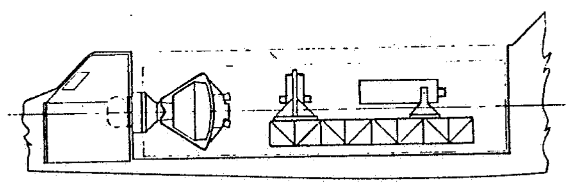


Figure 12. Escape Apollo CM in Orbiter Cargo Bay

3.0 SUPPORTING RESEARCH AND TECHNOLOGY REQUIREMENTS

The principal supporting research and technology requirements identified are presented below in the order of the five tasks performed during the study.

- The behavior of liquids, pressurized gases, and cryogenics should be studied to understand chemical, corrosion, explosion, and flammability characteristics in zero-g and vacuum or low-pressure environments.

- Means for detecting and suppressing fires in a zero-g pressurized environment should be investigated.

- Simulation studies of the dynamics and crew capabilities of the manipulator docking system should be conducted at the earliest possible time in order to understand the dynamic characteristics of the system and to identify and resolve hazards which are not apparent from conceptual studies. A safety analysis should be an integral part of such simulations.

- Pressure suits which can be quickly donned without prebreathing oxygen (8 psi suits) should be developed for use on the shuttle.

- The water stream and the stick-on rocket means of arresting the tumbling of out-of-control spacecraft should be studied further and a de-tumbling system developed in time for shuttle operations.

- The ability of crewmen to evaluate sensory cues in a tumbling spacecraft in space should be investigated by simulation and other tests. The objective would be to determine if untrained personnel can make the decisions necessary for their escape and rescue.

4.0 SUGGESTIONS FOR FURTHER EFFORT

The following suggestions are made for further study effort:

- The hazards associated with shuttle orbiter payloads and the measures required to control them should be studied for the prelaunch, launch, boost, deorbit, reentry, landing, and post-landing phases of shuttle missions.

- The behavior of fluids as they are spilled or released in a zero-g environment, both into vacuum and in pressurized environments, should be analyzed theoretically to obtain a comprehensive understanding of physical and chemical phenomena, and to identify potential hazards and areas of unknown.

- The dynamics of docking between vehicles with docking axes off-set from their centers of gravity should be analyzed to determine possible problem areas. Particular attention should be given to attitude control failures immediately before or after contact.

- At some appropriate time in the shuttle program a study should be initiated to determine whether escape or survivability capability will be required. The study should consider potential time criticalities of emergencies for the shuttle and its payloads; availability and time of shuttle rescue; and design and cost studies of the recommended escape and survivability concepts.

- The requirements and capabilities for mission abort, and for crew and passenger escape and rescue from the shuttle orbiter and manned payloads should be studied for the launch, boost, deorbit, reentry, landing, and post-landing phases. The objective should be to identify and recommend practical solutions consistent with the shuttle program. This task should be integrated with the solutions recommended for the on-orbit phases of escape and rescue.